ERCB/AGS Open File Report 2011-08

Tops of the Horseshoe Canyon, Wapiti and Battle Formations in the West-Central Alberta Plains: Subsurface Stratigraphic Picks and Modelled Surface

Energy Resources Conservation Board

Alberta Geological Survey

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Abstract

This report presents new subsurface stratigraphic picks for the tops of the Horseshoe Canyon, Wapiti and Battle formations in the west-central Alberta Plains (Townships 15 to 67, Ranges 16, West 4th Mer. to 3, West 6th Mer.) made using downhole geophysical well logs. Representative geophysical logs are included to demonstrate the criteria used to make picks and to highlight regional geological variability. Well data were screened to detect errors resulting from deviated wells, as well as incorrect ground and kelly-bushing elevation data. Statistical methods were used to identify local and regional statistical outliers, which were examined individually and either confirmed or removed. Detailed picking helped to delineate areas where the Battle Formation is absent and the top of the Horseshoe Canyon or Wapiti Formation coincides with the base of the overlying Scollard Formation. A structure contour map for the top of the Horseshoe Canyon and Wapiti formations is included to illustrate regional structure.

1 Introduction

In most areas (exceptions are noted in the following section), the two stratigraphic surfaces described in this report represent the top and base of the Battle Formation (Figure 1). This unit forms an important stratigraphic marker and regional aquitard (Bachu and Michael, 2002) in the nonmarine Upper Cretaceous succession across a wide area of west-central Alberta. An internally consistent set of stratigraphic picks for the base and top of the Battle Formation in the Alberta Plains is of potential use to a range of stakeholders who require detailed and accurate three-dimensional knowledge of the Upper Cretaceous bedrock. A structure contour map for the top of the underlying Horseshoe Canyon and Wapiti formations is included to illustrate regional structure.

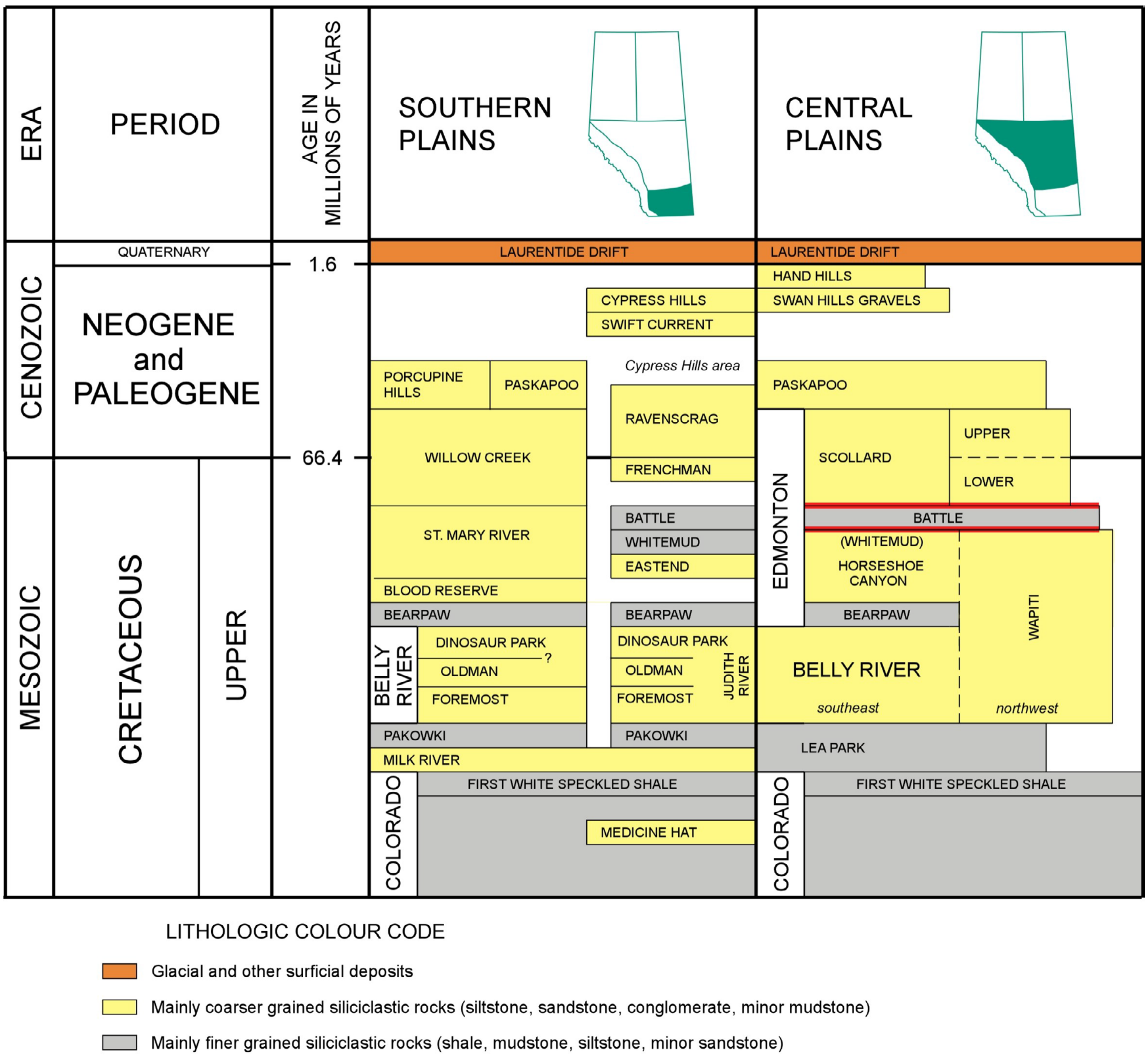

Figure 1. Schematic stratigraphic column for the Upper Cretaceous and Cenozoic in the central and southern Alberta plains. Red lines indicate stratigraphic surfaces dealt with in this report. Column is modified from Energy Resources Conservation Board (2009): modifications include the addition of the Dinosaur Park Formation as a constituent unit of the Belly River Group, and the downgrading of the Whitemud Formation to an informal unit at the top of the Horseshoe Canyon Formation following Hamblin (2004).

This report briefly outlines the geology of the Battle Formation and underlying and overlying units before describing the criteria used to make stratigraphic picks. It is not intended as a comprehensive geological review. Readers requiring more detailed information on the geology of the Battle, Horseshoe Canyon and Wapiti formations are directed to other publications (Elliott, 1960; Ower, 1960; Ritchie, 1960; Irish and Havard, 1968; Irish, 1970; Lerbekmo, 1985; Binda, 1992; Dawson et al., 1994a; Hamblin, 2004).

2 General Stratigraphy

The Battle Formation is present at outcrop and in the subsurface across a wide area of west-central Alberta and in a relatively small area of the Cypress Hills in southeastern Alberta and southwestern Saskatchewan (Figure 2). Between these two areas, all strata younger than the Belly River Group have been removed by erosion over the Bow Island (also known as Sweetgrass) Arch (Figure 2). Little downhole geophysical data is available for the Battle Formation on the Cypress Hills and that area is not considered further in this report.

Initially, the name Battle Formation was used only for that part of the unit exposed in the Cypress Hills (Furnival, 1946), and the type section proposed by Irish (1970) is located on Eagle Butte at the western edge of this area. In west-central Alberta, the unit was generally designated as the upper part of the 'Kneehills tuff zone' (Allan and Sanderson, 1945; Ower, 1960), but its correlation with the Battle Formation of the Cypress Hills on lithological grounds was widely recognized (e.g., Russell and Landes, 1940; Allan and Sanderson, 1945). Irish and Havard (1968) gave formation status to the Battle Formation across all of southern and central Alberta.

In west-central Alberta, the Battle Formation ranges in thickness from 0 to 18 m and is distinctive both at outcrop and in downhole geophysical well logs. It typically consists of dark purple-brown mudstone, with minor siltstone and rare sandstone, overlying sandstone or siltstone of the Horseshoe Canyon or Wapiti formation. In many areas, one or more grey silicified beds, known as the Kneehills tuff, are present in the upper part of the Battle Formation mudstone (Ritchie, 1960; Lerbekmo, 1985; Binda, 1992). The top of the Battle Formation is commonly referred to as the top of the Kneehills tuff zone in earlier literature (e.g., Elliott, 1960; Irish and Havard, 1968) and in current oil and gas industry usage.

An interval of white sandstone and siltstone immediately underlying the Battle Formation was formerly separated as the Whitemud Formation (Irish and Havard, 1968). However, Hamblin (2004) downgraded the status of this unit to an "informal pedogenically altered horizon" at the top of the Horseshoe Canyon Formation, and this change has been accepted in more recent studies (e.g., Eberth, 2010). In the northwest, the Bearpaw Formation, which serves to separate the underlying Belly River Group and the overlying Horseshoe Canyon Formation farther to the south, is absent, and here the strata underlying the Battle Formation are assigned to the Wapiti Formation (Figure 1). Dawson et al. (1994a, b) found the Battle Formation difficult to recognize both in outcrop and in the subsurface in this area (although picks made on the top of the Battle Formation are shown in Dawson et al., 1994b, Figure 24.14) and included equivalent strata in the Wapiti Formation. However, no such difficulty was encountered in this study (see representative wells below) and it is treated as a separate formation in that area in this report.

The Battle Formation is overlain by sandstone or siltstone of the Scollard Formation in west-central Alberta (Figure 1). In some areas (described in more detail below), the Battle Formation has been completely removed by erosion that predated deposition of the Scollard Formation, and Scollard Formation sandstone rests directly on the Horseshoe Canyon or Wapiti formation. With these exceptions, the Battle Formation can be traced to its present-day erosional edge in the north and east and to the limit of foothills deformation to the west. It can be mapped as a discrete unit in the subsurface as far south as Twp. 15 (see Section 5.3 below). South of Twp. 17, the units below and above the Battle Formation are mapped as the St. Mary River and Willow Creek formations, respectively (Hamilton et al., 1999).

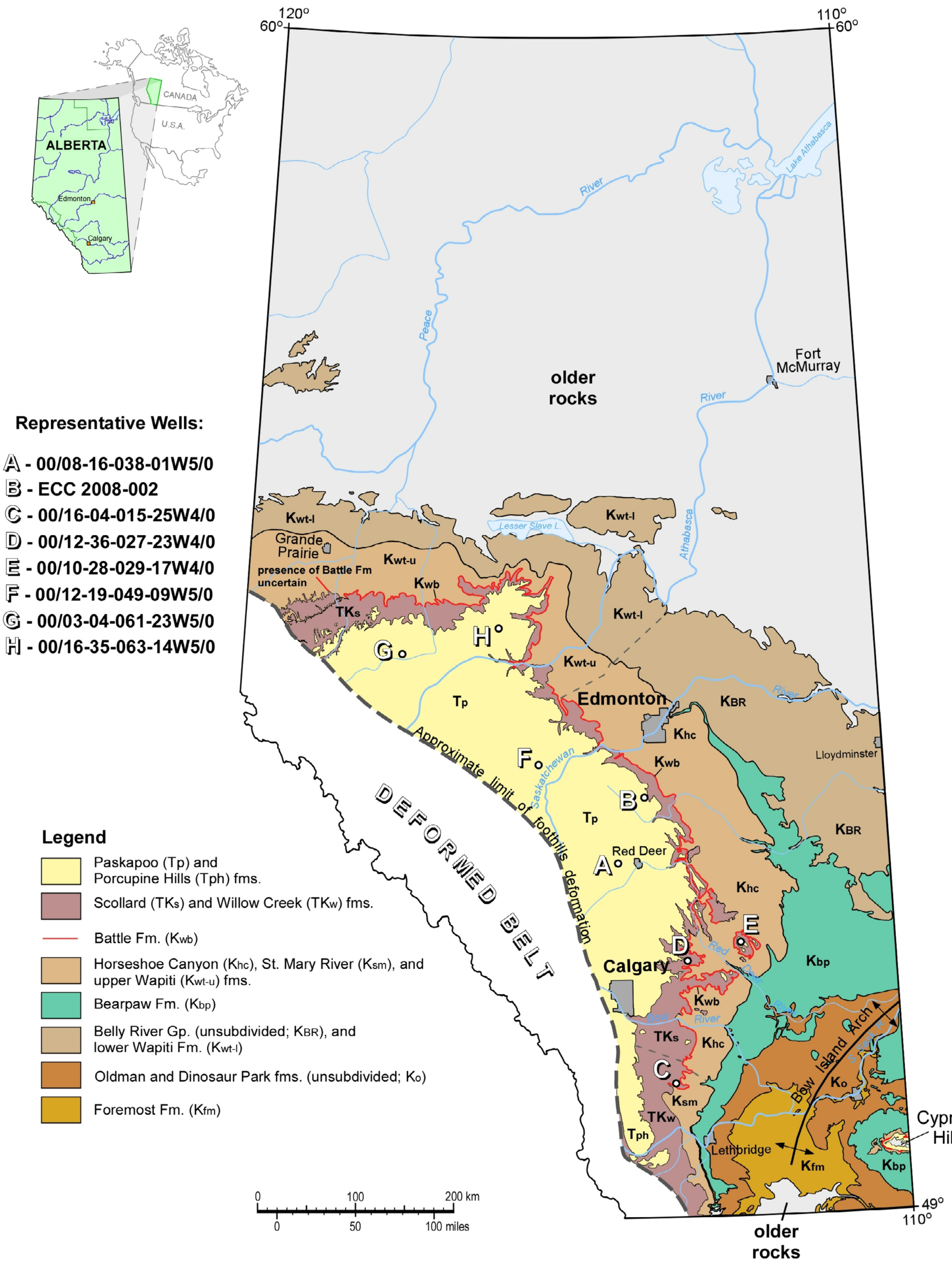

Figure 2. Simplified geological map (modified from Hamilton et al., 1999) showing the distribution of Horseshoe Canyon, Wapiti, Battle and Scollard formations and surrounding rocks in southern and central Alberta and the locations of representative wells figured in this report. Position of Bow Island Arch from Wright et al. (1994). Breaks in the red line marking the Battle Formation indicate areas where that formation is considered to be absent.

Although the Battle Formation (Irish and Havard, 1968) or a correlative interval (Tozer, 1952; Hamblin, 1998) has been identified farther south in outcrop at a single location on the Oldman River in Twp. 10, Rge. 25, West 4th Mer., the present author was unable to distinguish it as a separate unit south of Twp. 15 using downhole geophysical well logs.

3 Tops of the Horseshoe Canyon or Wapiti and Battle Formations

Most of the available data on these formation boundaries in west-central Alberta derives from outcrop along the Red Deer River valley in the Red Deer to Drumheller area.

Although Russell (1983) described the contact between the uppermost Horseshoe Canyon Formation (formerly Whitemud Formation) and the overlying Battle Formation as "transitional and alternating," there is a consensus in the more recent literature that the boundary represents a significant disconformity. Hamblin (2004) described the contact as sharp and unconformable, considering the "white, kaolin-rich sandstone" of the former Whitemud Formation to represent a "well-developed paleosol beneath the sub-Battle unconformity." Eberth (2010) described the boundary as a "significant unconformity characterized by channel-scale relief, and intense rooting and weathering on the Whitemud." Based on palynological and magnetostratigraphic data, Catuneanu and Sweet (1999) and Catuneanu et al. (2000) concluded that the contact between the Whitemud Formation (equivalent to the uppermost Horseshoe Canyon) and Battle Formation represents a significant early Late Maastrichtian hiatus and interpreted the disconformity as a third-order sequence boundary. Lerbekmo and Coulter (1985) found that the contact coincides closely with the 30r-30 magnetochron boundary at a number of outcrop sections in the Red Deer River valley, showing it to be the best lithological time marker in those sections below the Scollard Formation.

There have been differing views on the nature of the contact between the Battle Formation and the overlying Scollard Formation. Irish and Havard (1968) noted that "the upper contact (of the Battle Formation) appears conformable at most places but, at others, it is definitely unconformable," and that "at some localities…the Battle Formation has been partly to wholly removed by erosion and its place taken by grey, medium- to coarse-grained, buff-weathering (Scollard Formation) sandstone." Similarly, Gibson (1977) stated that "the Battle Formation is overlain conformably at most localities in the report-area (the Red Deer River valley) by olive- to greenish-grey weathering silty to sandy mudstone of the Scollard Formation. The contact generally is abrupt and readily apparent. However, at some sections it is gradational within a thin stratigraphic interval of 1.5 m." Gibson (1977) also noted that locally, part or all of the Battle Formation mudstone has been eroded beneath channel sandstones at the base of the Scollard Formation.

Russell (1983) presented evidence for a regional disconformity at the base of the Scollard Formation. He suggested that "a time break at the Scollard-Battle contact is indicated by: 1) irregularities of the contact surface; 2) wide variations in thickness of the lower Scollard beds above the contact; 3) abrupt change of fauna, particularly the dinosaurs, from the Horseshoe Canyon Formation to the Scollard Formation; and 4) presence of an analogous unconformity between the St. Mary River and Willow Creek formations to the southwest, and between the Battle and Frenchman formations in the Cypress Hills and eastward, in both cases with evidence of erosion." He noted that the "passage from…Whitemud to Battle beds (is) transitional and alternating, whereas the change from Battle to Scollard is a sharp boundary, even where evidence of post-Battle erosion is absent. Thus, if the paleontological break is to be associated with a stratigraphic boundary, it should be with the Scollard-Battle contact, rather than with lower, more or less arbitrary boundaries."

However, Lerbekmo (1985) agreed with Gibson (1977), stating that "no regional disconformity exists at this level in the Red Deer River valley area. At most, a very few metres of local scour may occur below basal Scollard channel sandstones." This view was supported by Catuneanu et al. (2000), who suggested that in contrast to the major early Late Maastrichtian stratigraphic gap at the base of the Battle Formation, there was a relatively continuous stratigraphic record for the late Late Maastrichtian to middle Early Paleocene Battle Formation–Scollard Formation interval. However, Koppelhus and Braman (2010) have recently suggested that a mixed palynomorph assemblage in the lowest portion of the Scollard Formation adds support to the presence of an unconformity below the basal Scollard Formation sandstone.

Whatever the true significance of the Battle Formation–Scollard Formation contact, it is certainly erosional in some areas and, as noted in outcrop by Irish and Havard (1968) and Gibson (1977), the Battle Formation has locally been completely removed by erosion. Figure 3 shows the distribution of wells in which the Battle Formation is absent and the Scollard Formation rests directly on the Horseshoe Canyon or Wapiti Formation. They occur within a number of well-delineated base-of-Scollard Formation paleovalley systems (Hathway and Mei, 2010), which trend southeast in the Calgary to Red Deer area, broadly along the present trends of the Bow and Red Deer rivers, and north-northeast in the area of the present Athabasca River.

4 Picking Criteria

The Battle Formation has been described as an "almost unbelievably continuous marker" (Elliott, 1960) in the subsurface. The gamma-ray signature is generally high, but irregular and spiky. In some wells (e.g., representative well 00/10-28-029-17W4/0 below), an abrupt decrease in gamma-ray API upward may sharply delineate the top of the formation, but elsewhere the gamma-ray curve may be less helpful (see well 00/08-16-038-01W5/0 below). The Battle Formation has a characteristically low-resistivity signature, which is usually the best guide to its position. However, the base of the formation may be difficult to pick with precision on resistivity curves (see well 00/10-28-029-17W4/0 below). Upper and lower contacts are therefore best picked at the sharp upward deflections to the left (base of the Battle Formation) and right (top of the formation) on neutron, density and sonic curves, ideally in combination with similar deflections on a resistivity log. Where resistivity logs are unavailable, as in the cased-hole (usually gamma ray, sonic and neutron) log suites commonly run in wells drilled for coalbed methane (e.g., Lewis, 2006) or where the Battle Formation is shallow and behind surface casing (see well 00/12-36-027-23W4/0 below), picks can be made using neutron and/or sonic logs.

As noted by Dawson et al. (1994b), the Battle Formation can generally be recognized by its position relative to coal zones present within the underlying Horseshoe Canyon and Wapiti formations (Carbon-Thompson and Cutbank coal zones) or the overlying Scollard Formation (Ardley coal zone). Logs from one of the several wells that provided core control on the Battle Formation in this study are illustrated and described below (see well ECC 2008-02).

In the present study, wells were never picked in isolation, but always on cross-section, with an average well spacing of 1 km (maximum 13 km). In some areas, a much smaller well spacing was used. This was particularly useful in delineating areas where the Battle Formation thins or has been completely removed by erosion at the base of the Scollard Formation (see Section 5.9 below).

5 Representative Wells

The representative wells detailed below were chosen to

- illustrate regional variations in the log signature at the tops of the Horseshoe Canyon, Wapiti and Battle formations in west-central Alberta,
- illustrate the variation in picking criteria depending on which logs are available in a given well (e.g., logs run through casing) and
- give an example of core control on the downhole position of the Battle Formation.

Figure 2 shows the well locations.

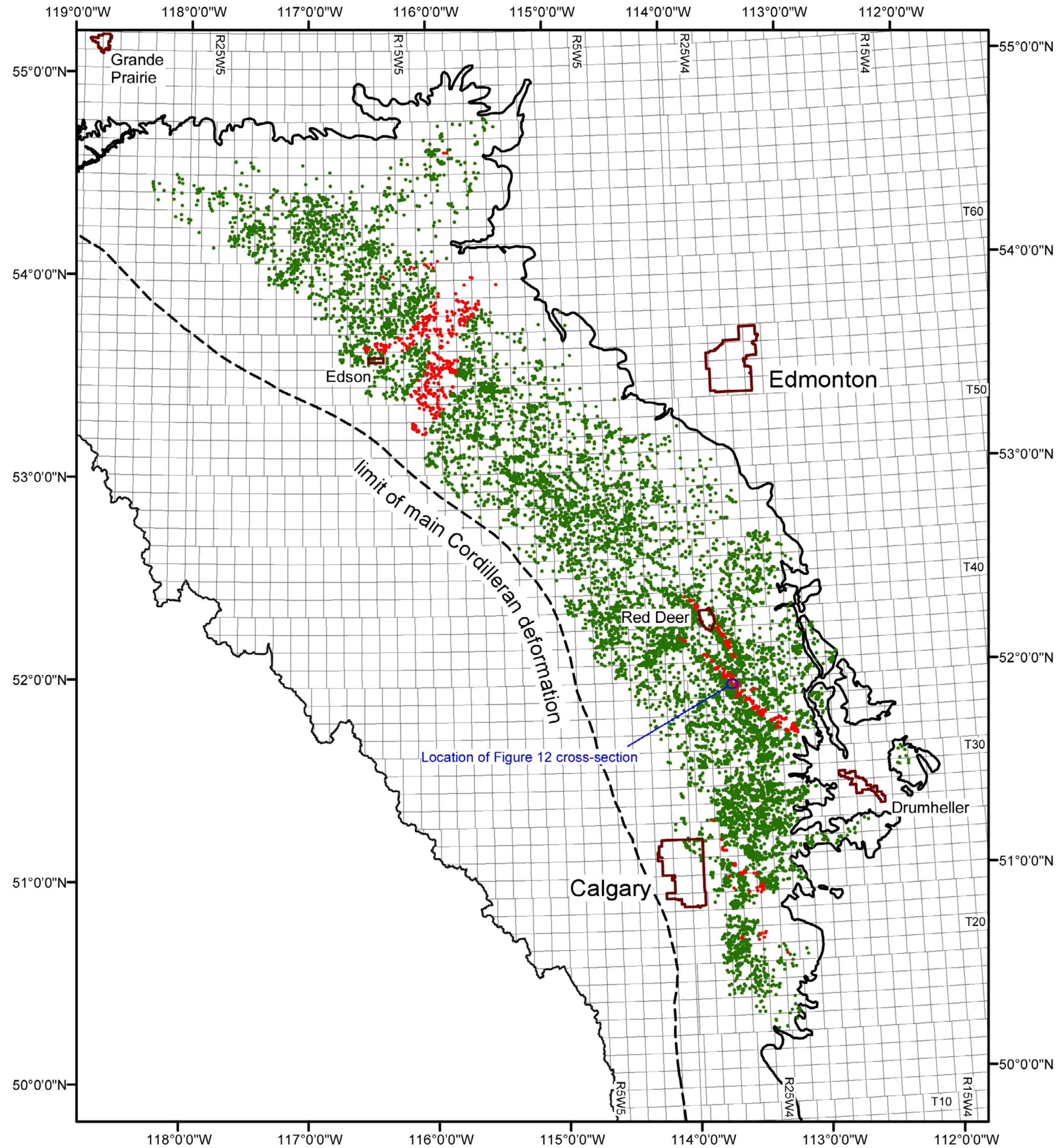

Figure 3. Distribution of wells used in this study (west-central Alberta Plains). Wells in which the Battle Formation is present are highlighted in green and wells in which that unit is absent are highlighted in red. Solid black line marks the mapped top of the Horseshoe Canyon (St. Mary River Formation south of Twp. 17) and Wapiti formations from Hamilton et al. (1999). Major urban areas are outlined in dark brown.

5.1 Red Deer Area (00/08-16-038-01W5/0)

Well 00/08-16-038-01W5/0 is the Battle Formation reference well, situated 20 km west of Red Deer, shown in Figure 24.10 of the 1994 Geological Atlas of the Western Canada Sedimentary Basin (Dawson et al., 1994b). As noted by Dawson et al. (1994b), the Battle Formation is easily recognized by its low-resistivity log response and its proximity to the underlying Carbon-Thompson coal zone (Figure 4). Upper and lower contacts are picked at the sharp upward deflections to the left (base of the Battle Formation) and right (top of the formation) on the neutron, density and sonic logs, in combination with similar deflections on the resistivity curves.

5.2 Wetaskiwin Area (ECC 2008-02)

Well ECC 2008-002, situated 21 km west-southwest of Wetaskiwin, was drilled as part of the AGS Edmonton–Calgary Corridor groundwater mapping program (Riddell et al., 2009). It provides core control on the Battle Formation, which consists here of 7.6 m of dark purple–brown to black, slightly silty, organic-rich mudstone, overlain with a sharp contact by grey-green siltstone of the Scollard Formation and underlain by the silty top of a pale grey, 4.5 m thick, fining-upward (coarse grained at the base) sandstone unit at the top of the Horseshoe Canyon Formation. The low-resistivity log response of the Battle Formation is again clear (Figure 5) and, as before, upper and lower contacts of the unit are picked at the sharp upward deflections to the left (base) and right (top) on the neutron, density and sonic curves, in conjunction with similar deflections on the resistivity logs.

5.3 Vulcan Area (00/16-04-015-25W4/0)

Well 00/16-04-015-25W4/0, situated 20 km south-southwest of Vulcan, is the southernmost well in which the base and top of the Battle Formation can be confidently identified. In this area, south of Twp. 17, underlying and overlying strata are respectively mapped as the St. Mary River and Willow Creek formations (Hamilton et al., 1999), stratigraphically equivalent to the Horseshoe Canyon and Scollard formations to the north. The low-resistivity log signature of the Battle Formation is still distinct on the deep induction log and its upper and lower contacts are again picked using a combination of neutron, density, sonic and induction logs (Figure 6). An interval above the Battle Formation that shows a similar log response to the Battle Formation (although here the resistivity is not so low) is typically present in this area. In well 00/16-04-015-25W4/0, this interval lies approximately 6 m above the top of the Battle Formation (between 260 and 274 m below kelly bushing [KB]), but farther south it merges with the Battle Formation, which can no longer be defined as a distinct unit using geophysical well logs.

5.4 Drumheller Area (00/12-36-027-23W4/0)

In well 00/12-36-027-23W4/0, situated 30 km west-southwest of Drumheller, the Battle Formation is shallow (top at 34.4 m measured depth) and behind surface casing. Only gamma-ray, sonic and neutron logs are available (Figure 7). The Battle Formation shows a variable gamma-ray signature, which is elevated in the lower part, but is not clear enough to pick contacts. However, the formation boundaries can be picked at the sharp deflections on the neutron and sonic logs. In wells such as these, picking on cross-sections with a small well spacing is necessary and the position of the underlying Carbon-Thompson coal zone can be a valuable guide to identifying the Battle Formation.

5.5 Hand Hills (00/10-28-029-17W4/0)

Well 00/10-28-029-17W4/0 is situated in the Hand Hills, 26 km east of Drumheller. The Battle Formation shows its characteristic low-resistivity signature, in this case with uniformly high gamma-ray counts (Figure 8). The top of the Battle Formation is clear at the sharp upward deflections to the right on the density, neutron and resistivity curves and to the left on the gamma-ray curve. The top of the Horseshoe Canyon Formation can be placed approximately using the resistivity and gamma-ray logs, but can be picked more precisely at the sharp upward deflection to the left on the neutron curve.

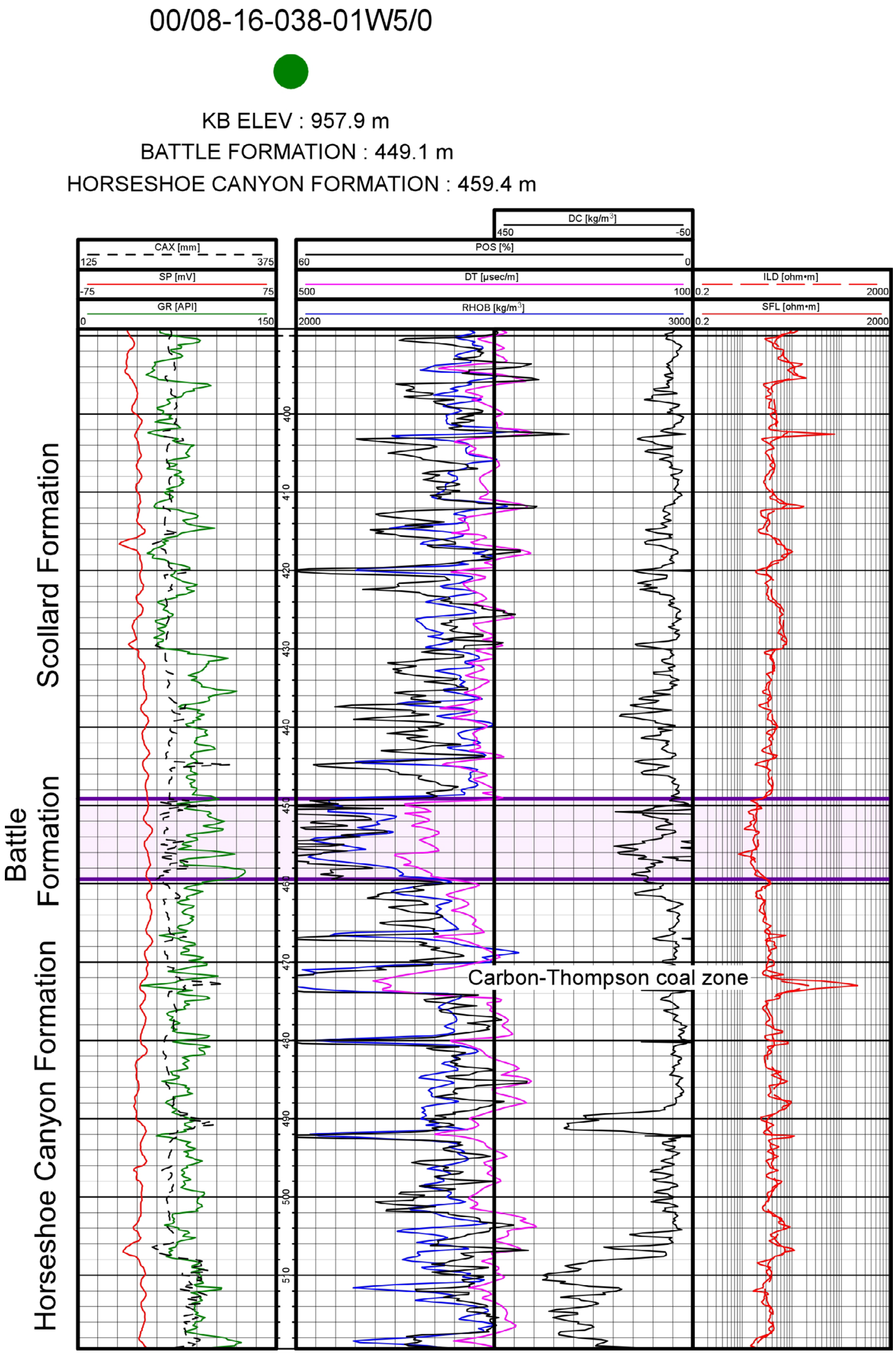

Figure 4. Caliper (CAX in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DC in kg/m³), borehole compensated (BHC) sonic (DT in µsec/m), bulk density (RHOB in kg/m³), neutron-porosity (sandstone; POS in %), deep induction (ILD in ohm•m) and spherically focused resistivity (SFL in ohm•m) logs for Dawson et al. (1994b) reference well (00/08-16-038-01W5/0), situated 20 km west of Red Deer, Alberta. The tops of the Horseshoe Canyon and Battle formations are indicated. Vertical scale is measured depth in metres below kelly bushing (KB). KB elevation is in metres above sea level. Other abbreviation: ELEV, elevation.

ECC2008-002

KB ELEV: 819.4 m
BATTLE FORMATION: 97.9 m
HORSESHOE CANYON FORMATION: 105.5 m

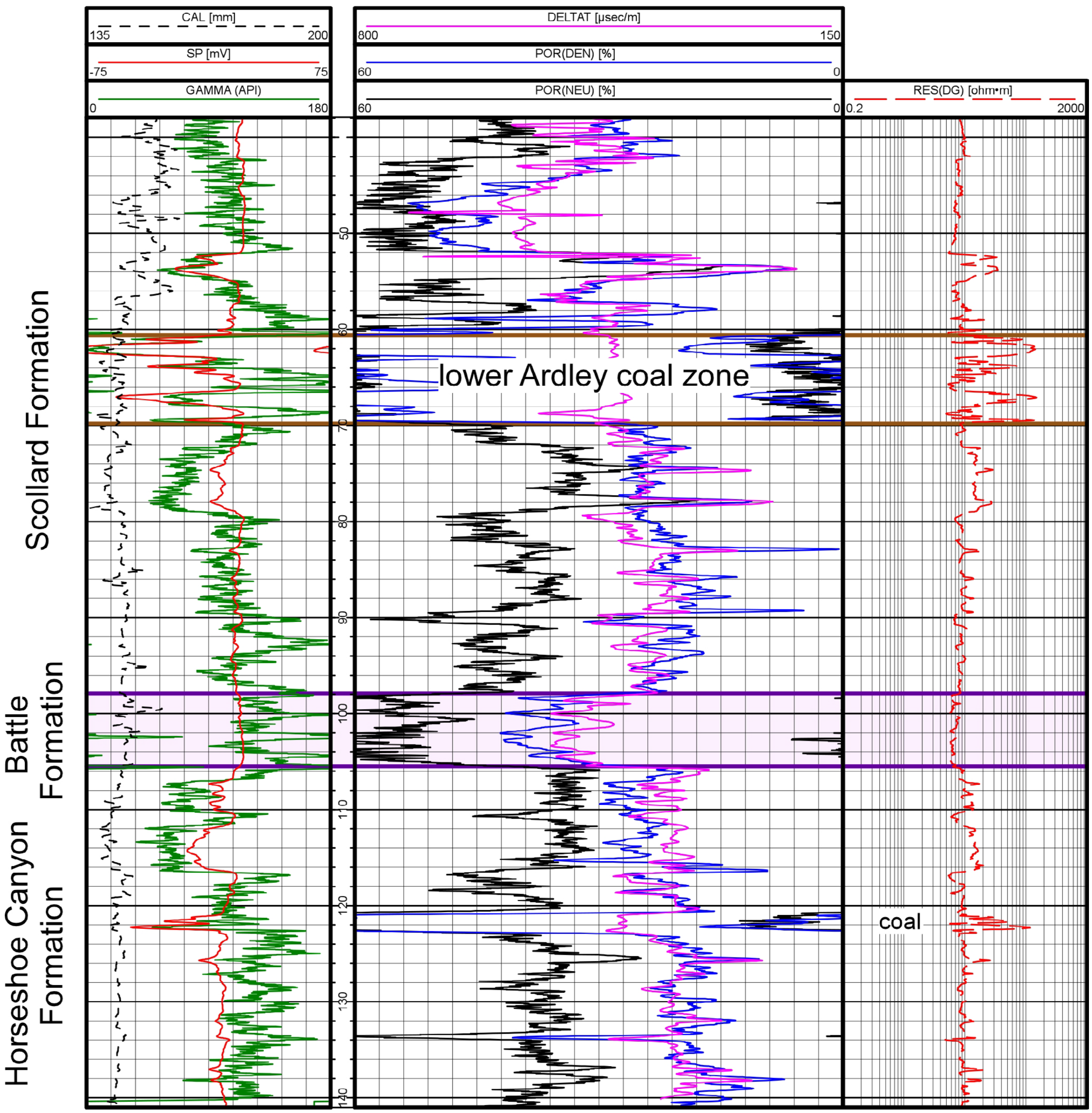

Figure 5. Caliper (CAL in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), neutron-porosity (POR(NEU) in %), density-porosity (POR(DEN) in %), sonic (DELTAT in µsec/m) and deep guard resistivity (RES(DG) in ohm•m) logs for Alberta Geological Survey Edmonton–Calgary Corridor groundwater project well (ECC 2008-002), situated 21 km west-southwest of Wetaskiwin, Alberta. Vertical scale is measured depth in metres below kelly bushing (KB). KB elevation is in metres above sea level. Other abbreviation: ELEV, elevation.

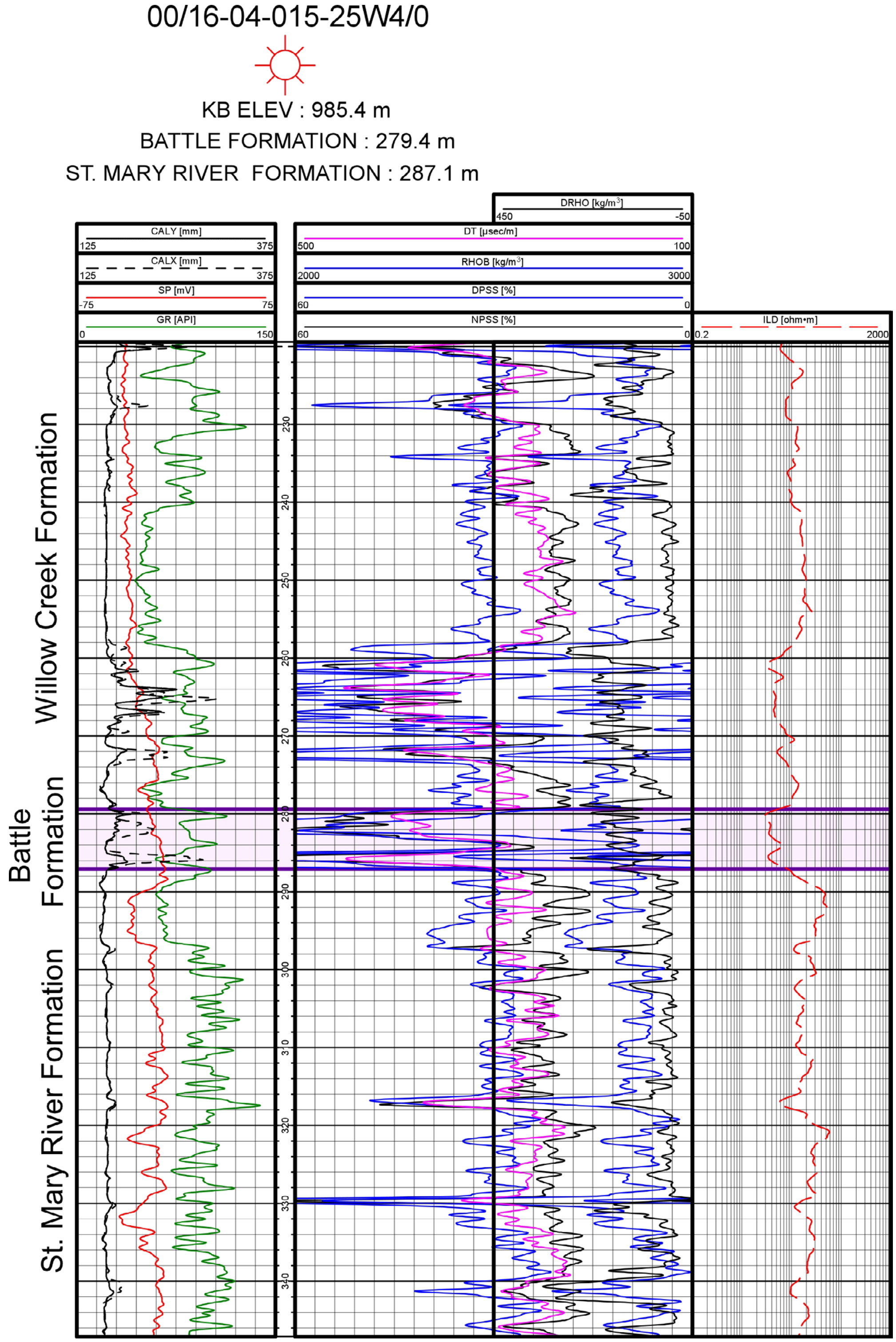

Figure 6. Caliper (CALY and CALX in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DRHO in kg/m³), neutron-porosity (sandstone; NPSS in %), density-porosity (sandstone; DPSS in %), borehole compensated (BHC) sonic (DT in µsec/m) and deep induction (ILD in ohm•m) logs for well (00/16-04-015-25W4/0) at southernmost limit of identifiable Battle Formation in the subsurface, 20 km south-southwest of Vulcan, Alberta. Vertical scale is measured depth in metres below kelly bushing (KB). KB elevation is in metres above sea level. Other abbreviation: ELEV, elevation.

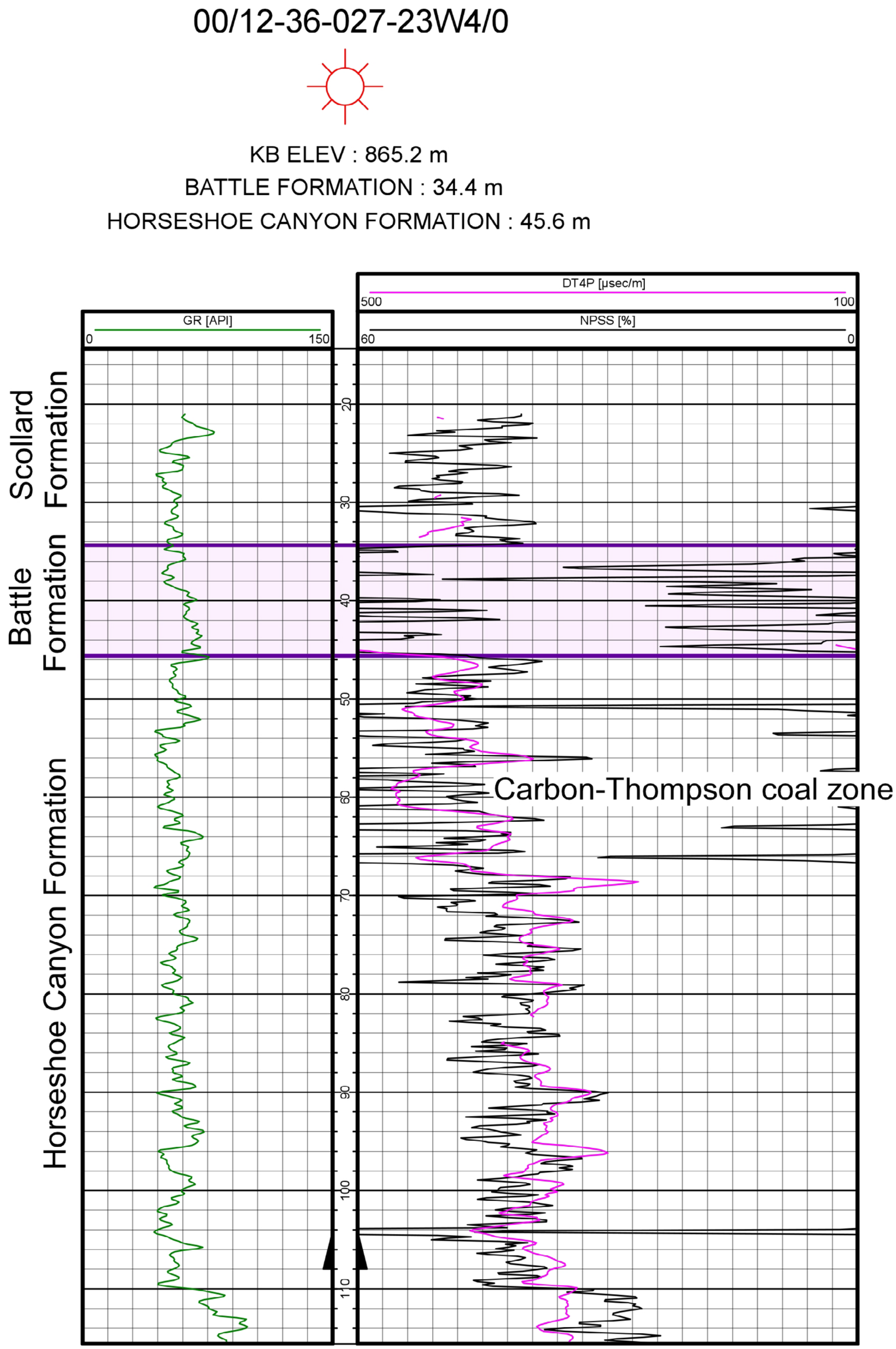

Figure 7. Gamma-ray (GR in API units), dipole sonic (DT4P in µsec/m) and neutron-porosity (sandstone; NPSS in %) logs for well (00/12-36-027-23W4/0) situated 30 km west-southwest of Drumheller, Alberta. Battle Formation is behind surface casing (shoe at 108 m). Vertical scale is measured depth in metres below kelly bushing (KB). KB elevation is in metres above sea level. Other abbreviation: ELEV, elevation.

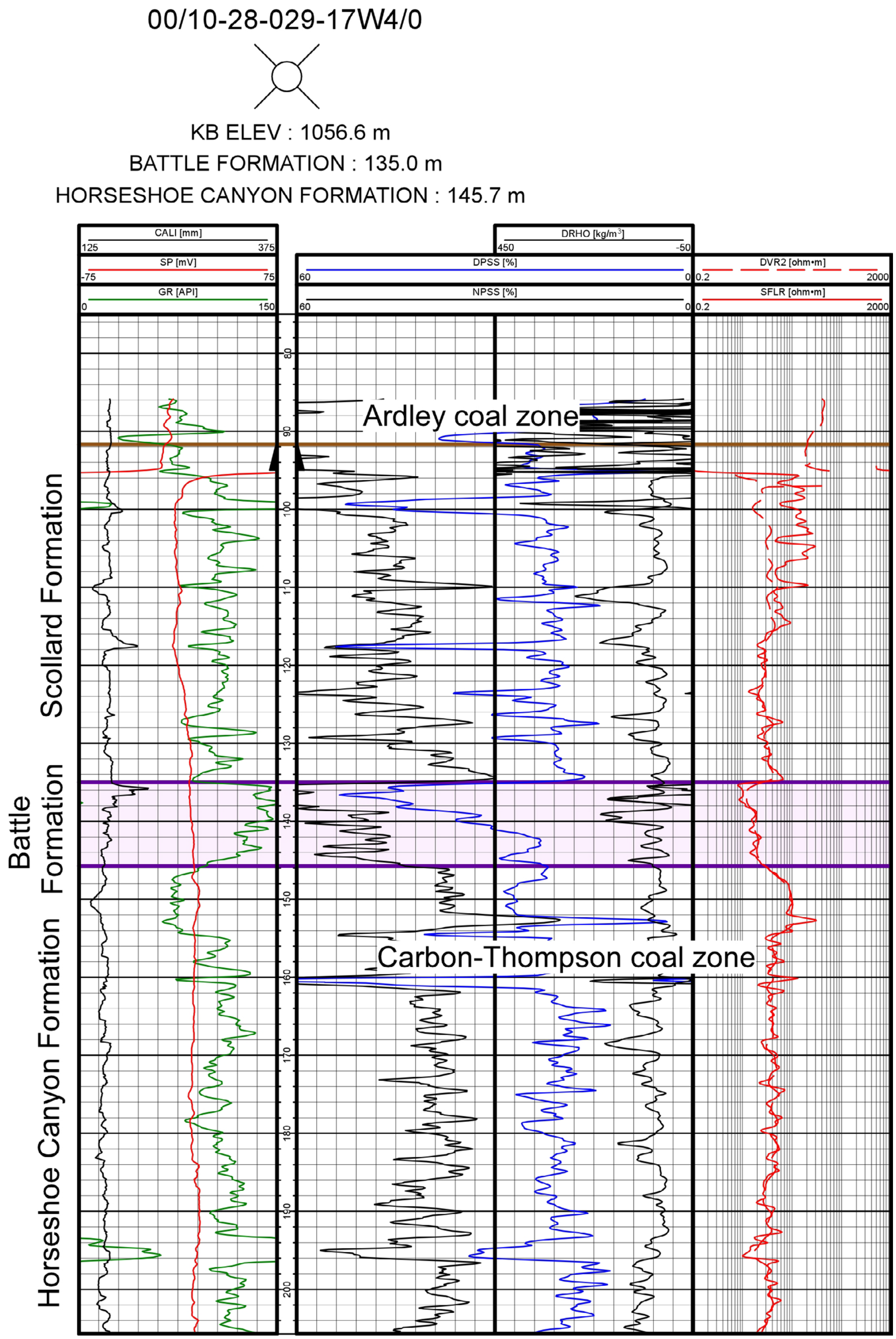

Figure 8. Caliper (CALI in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DRHO in kg/m^3), density-porosity (sandstone; DPSS in %), neutron-porosity (sandstone; NPSS in %), deep resistivity (DVR2 in ohm•m) and spherically focused resistivity (SFLR in ohm•m) logs for representative well (00/10-28-029-17W4/0) in the Hand Hills, 26 km east of Drumheller, Alberta. Vertical scale is measured depth in metres below kelly bushing (KB). KB elevation is in metres above sea level. Other abbreviation: ELEV, elevation.

5.6 Drayton Valley Area (00/12-19-049-09W5/0)

The Battle Formation shows a typical log signature in well 00/12-19-049-09W5/0 (Figure 9), situated 22 km west of Drayton Valley. Gamma-ray counts are high, but the log response is erratic and spiky. As before, upper and lower contacts of the unit are picked at the sharp upward deflections to the left (base) and right (top) on the neutron, density and sonic curves, in conjunction with similar deflections on the resistivity log.

5.7 Fox Creek Area (00/03-04-061-23W5/0)

Well 00/03-04-061-23W5/0 is situated 42 km west-southwest of Fox Creek, in the northwestern subcrop area of the Battle Formation. The Battle Formation shows its characteristic low-resistivity log response and gamma-ray counts are high but erratic (Figure 10). The formation boundaries can be picked with some precision at the sharp upward deflections to the left (top of Wapiti Formation) and right (top of Battle Formation) on the sonic and resistivity curves. The presence of a thick (here 14 m) sandstone interval at the top of the Wapiti Formation is characteristic in this area. Above the Battle Formation, the basal Scollard Formation typically shows a spiky log signature indicating a thinner bedded succession of sandstone and finer grained intervals.

5.8 Swan Hills (00/16-35-063-14W5/0)

Well 00/16-35-063-14W5/0 is situated in the Swan Hills, 43 km north-northwest of Whitecourt, in the northernmost subcrop area of the Battle Formation. Only gamma-ray, spontaneous potential (SP), caliper and resistivity logs are available for this well (Figure 11). Although the caliper log indicates that intervals within the Battle Formation have washed out, its characteristic low-resistivity, high–gamma-ray signature remains clear. In the absence of neutron, density or sonic logs, the upper and lower contacts of the Battle Formation were picked at the top and bottom of the low-resistivity interval. Log responses of the uppermost Wapiti Formation and lower Scollard Formation are similar to those seen in the Fox Creek area well described above.

5.9 Cross-Section Showing Thinning and Local Absence of the Battle Formation

A southwest–northeast stratigraphic cross-section (Figure 12; datum is the base of the Ardley coal zone in the Scollard Formation), situated 38 km south-southeast of Red Deer in Twp. 34, Rge. 26, West 4th Mer. illustrates thinning and local removal of the Battle Formation beneath the Scollard Formation. The Battle Formation thins to the northeast beneath a thickening basal Scollard Formation sandstone interval and is eventually cut out completely. Although it may be possible to pick a definite top for the Horseshoe Canyon or Wapiti Formation where the Battle Formation has been completely removed (as in the two wells to the right), in many cases basal Scollard Formation and uppermost Horseshoe Canyon (Whitemud) or Wapiti Formation sandstone intervals are amalgamated (as in well 00/15-22-034-26W4/0, third from right) and no definite pick can be made.

6 Dataset and Methods

The data from this study are presented in Digital Dataset 2011-0002 (Hathway, 2011), which includes new stratigraphic picks for the top of the Horseshoe Canyon and Wapiti formations from 8863 wells and for the top of the Battle Formation from 8145 wells. The data for the Horseshoe Canyon and Wapiti formations includes some picks in the area south of Twp. 17, where strata stratigraphically equivalent to the Horseshoe Canyon Formation are currently mapped as St. Mary River Formation (Hamilton et al., 1999). Wells in which the Battle Formation is absent are noted as such in the dataset. These include 28 wells in which no definite top for the Horseshoe Canyon or Wapiti Formation could be picked (Battle Formation noted as absent, but no associated Horseshoe Canyon or Wapiti Formation pick in the dataset). The dataset is in the zip file that accompanies the PDF of this report at http://www.ags.gov.ab.ca/publications/abstracts/OFR_2011_08.html.

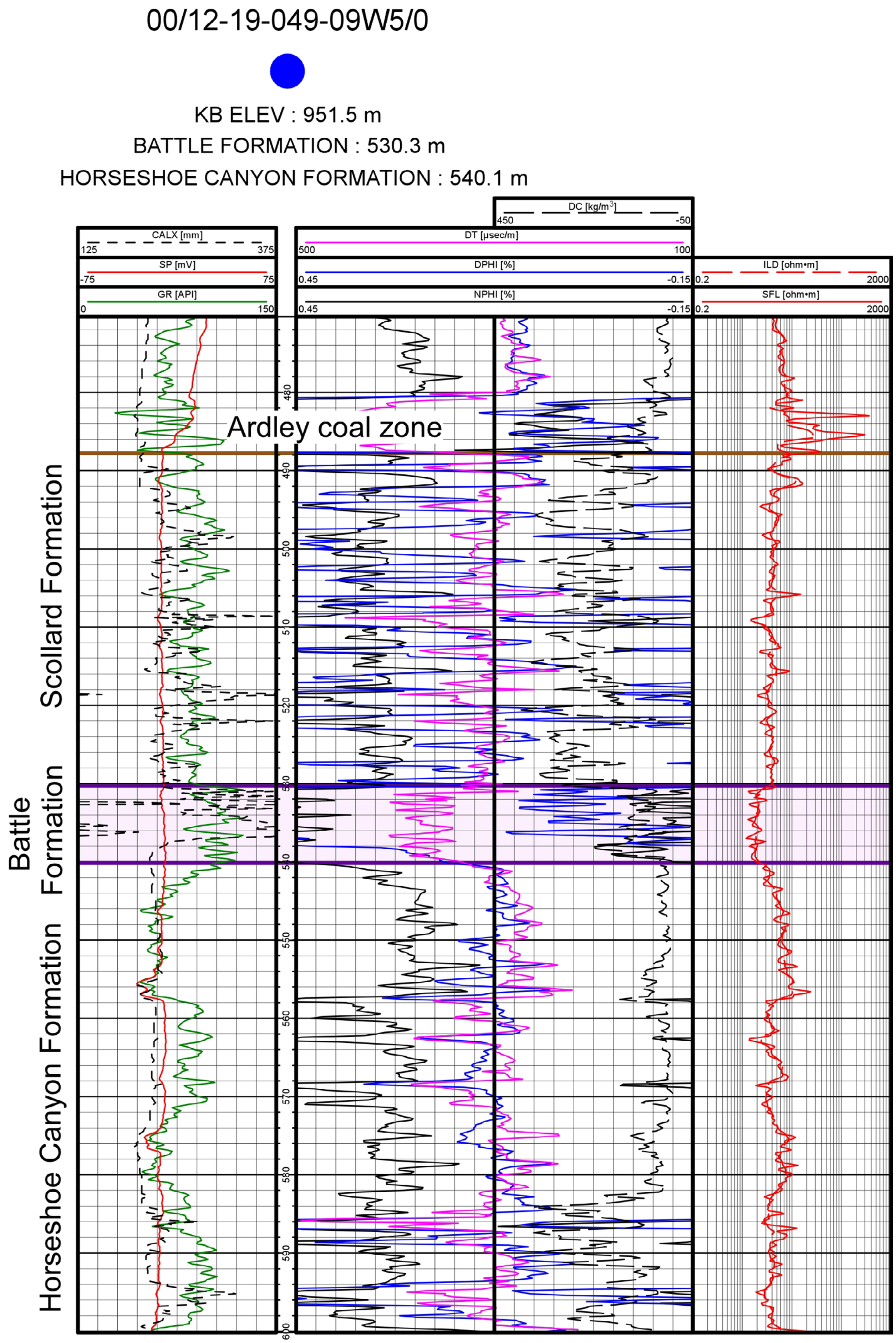

Figure 9. Caliper (CALX in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DC in kg/m³), borehole compensated (BHC) sonic (DT in µsec/m), density-porosity (DPHI in %), neutron-porosity (NPHI in %), deep induction (ILD in ohm•m) and spherically focused resistivity (SFL in ohm•m) logs for representative well (00/12-19-049-09W5/0) situated 22 km west of Drayton Valley, Alberta. Vertical scale is measured depth in metres below kelly bushing (KB). KB elevation is in metres above sea level. Other abbreviation: ELEV, elevation.

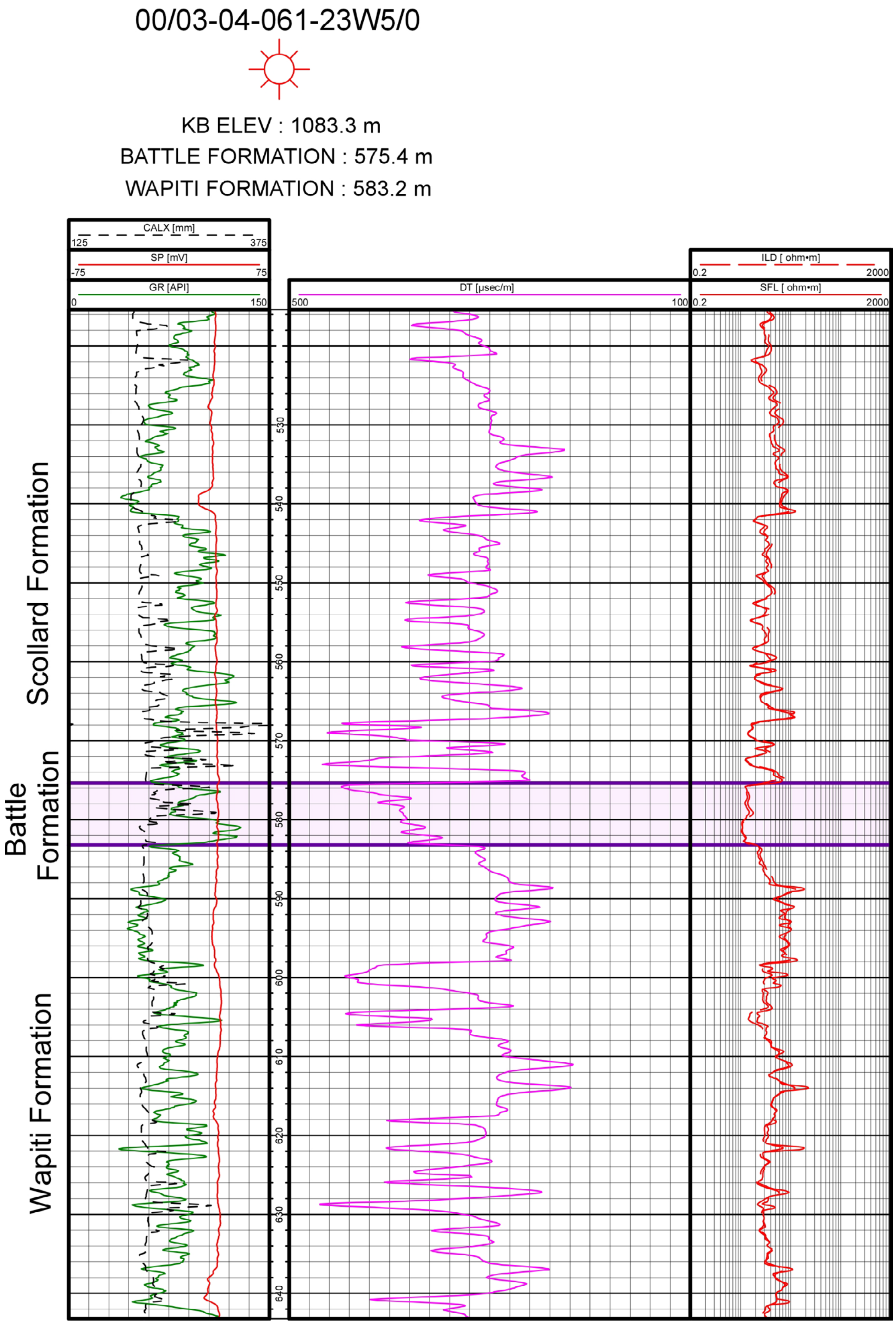

Figure 10. Caliper (CALX in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), borehole compensated (BHC) sonic (DT in µsec/m), deep induction (ILD in ohm•m) and spherically focused resistivity (SFL in ohm•m) logs for representative well (00/03-04-061-23W5/0) situated 42 km west-southwest of Fox Creek, Alberta. Vertical scale is measured depth in metres below kelly bushing (KB). KB elevation is in metres above sea level. Other abbreviation: ELEV, elevation.

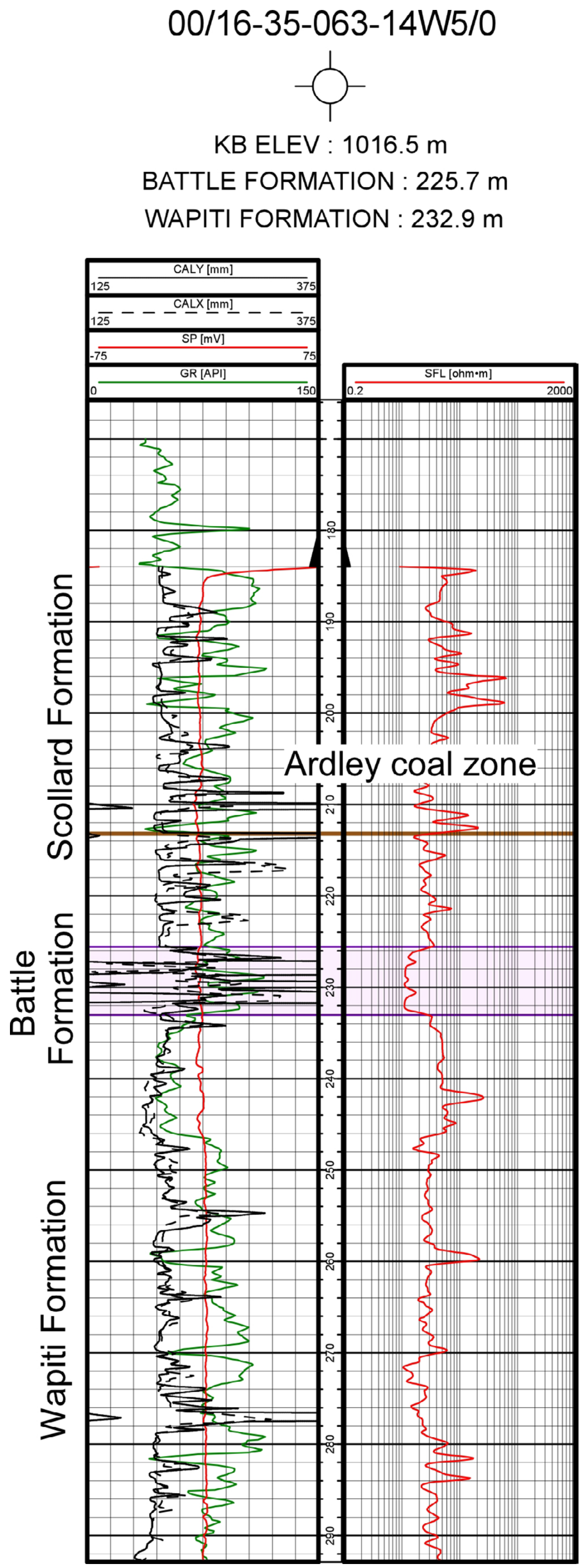

Figure 11. Caliper (CALY and CALX in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units) and spherically focused resistivity (SFL in ohm•m) logs for representative well in the Swan Hills (00/16-35-063-14W5/0), 43 km north-northwest of Whitecourt, Alberta. Vertical scale is measured depth in metres below kelly bushing (KB). KB elevation is in metres above sea level. Other abbreviation: ELEV, elevation.

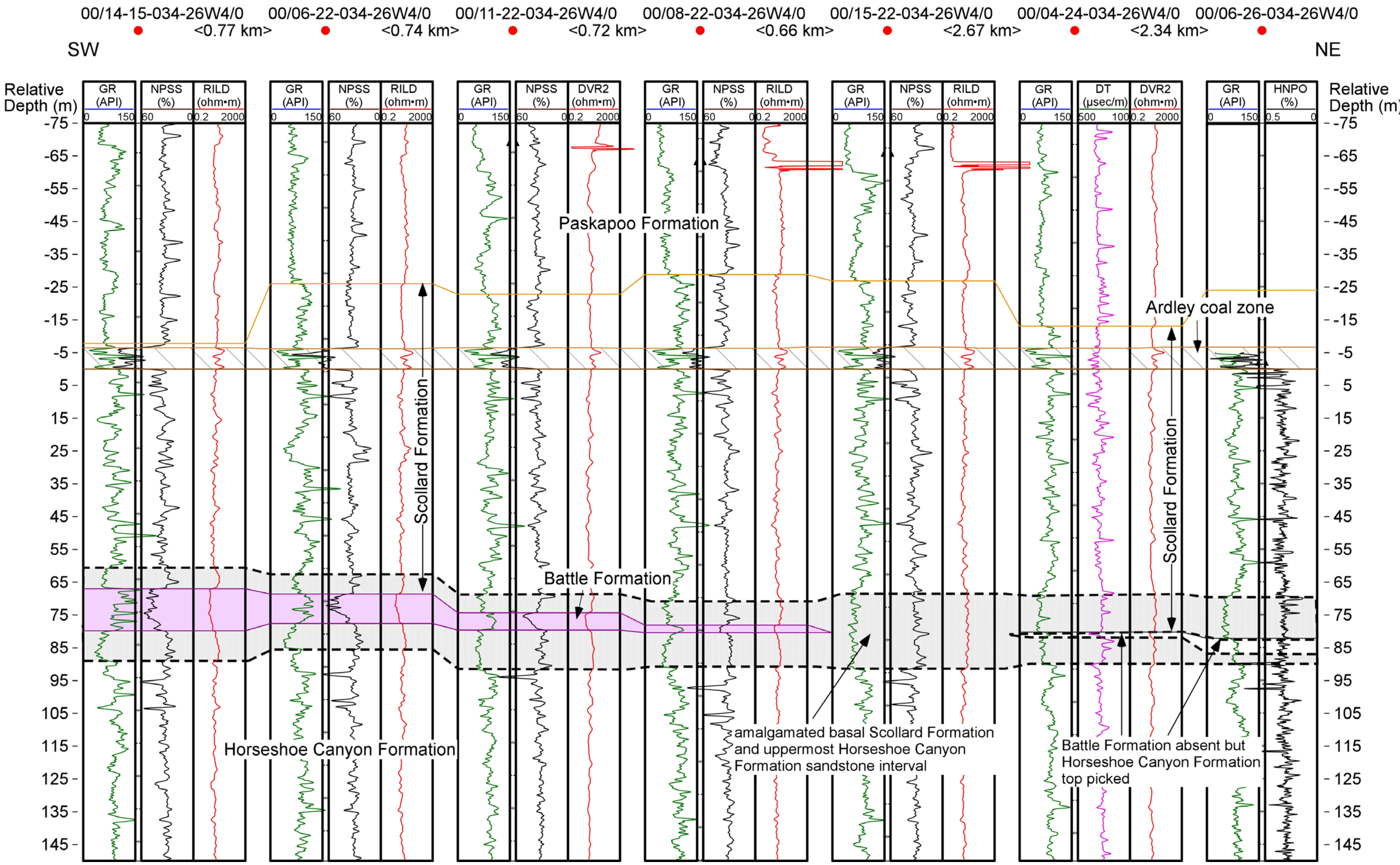

Figure 12. Southwest–northeast stratigraphic cross-section, situated 38 km south-southeast of Red Deer in Twp. 34, Rge. 26, West 4th Mer., illustrating thinning and local removal of the Battle Formation at the base of the Scollard Formation. Vertical scale in metres above and below datum, which is at the base of the Ardley coal zone in the Scollard Formation. Logs shown are gamma-ray (GR in API units), neutron-porosity (NPSS or HNPO in %), sonic (DT in µsec/m) and resistivity/induction (RILD and DVR2 in ohm•m). Purple shade indicates Battle Formation. Grey shade indicates sandstone in the uppermost Horseshoe Canyon and lowermost Scollard formations. Location of section shown in Figure 3.

Prior to making picks for a given surface, the published geological literature was studied with emphasis on representative sections. Where available, outcrop sections and drillcore (with associated geophysical well logs) were examined to provide a link between the rock and downhole geophysical signatures.

Geophysical well logs (both digital and raster format) were examined using Petra® and Accumap® software and picks were recorded in a database. Where well density and log availability were sufficient, wells were selected according to the following criteria:

1) vertical wells only
2) wells with a spud date between 1975 and the present
3) wells with downhole geophysical well-log suites that include gamma-ray; neutron, density or sonic; and resistivity logs. As previously noted, this requirement was relaxed in areas where the Battle Formation is close to surface and logs were obtained through casing.

A minimum well density of one well per township was aimed for, although well density greatly exceeds that number in most areas. Data tends to be sparser where the Battle Formation is shallow and in these areas all available wells were picked. Picks were made in wells from approximately 655 townships, resulting in an average density of approximately 13.5 wells per township for the top of the Horseshoe Canyon and Wapiti formations.

To facilitate correlation, wells were never picked in isolation, but always on cross-section, with a maximum well spacing of 13 km. In most areas, a much smaller well spacing was used. During the process, picks were gridded using Petra software to identify and check outliers, which appear as 'bull's-eyes' on a structure contour map.

7 Quality Control Procedures

After making picks and prior to modelling the surface, steps were taken to eliminate or minimize errors resulting from

- incorrect depth data (well deviation),
- incorrect well-header KB elevation data,
- incorrect well-header ground elevation data and
- incorrect pick depth (due to human error).

Picks and well-header information, including KB elevation, ground elevation, surface location (longitude and latitude in decimal format) and bottom-hole location (longitude and latitude in decimal format), were exported from Petra (IHS) software into a comma-separated value file. The datum for the well location is NAD 83 and the picks are in metres, given as measured depth relative to KB elevation. Pick elevations, relative to sea level, were calculated by subtracting measured depth (MD) from the KB elevation.

A query of the well surface location compared with the bottom-hole location was run to check for any deviations from vertical. If a well is deviated, its surface and bottom-hole co-ordinates should be different. These wells were removed from the dataset. As all remaining wells should be vertical if the surface and bottom-hole co-ordinates are correct, measured depth and true vertical depth should be equal.

Although incorrect KB elevation data can be difficult to detect, the data were screened by comparing the ground elevation and the KB elevation (equal to the derrick-floor height) for each well. An acceptable range of derrick-floor height—calculated by subtracting ground elevation from KB elevation—of 2 to 6 m was used. Wells with derrick-floor heights outside this range were excluded.

To check for potential gross errors in the ground elevation of wells, well-header ground elevations were compared with Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) data (United

States Geological Survey, 2000) extracted for well surface locations. If the difference obtained by subtracting the well-header ground elevation from the elevation derived from the DEM was more than 2 ±9 m (i.e., –7 to 11 m; approximately the mean of this difference plus or minus three standard deviations for all wells in the Alberta Plains) that well was excluded. This method potentially excluded wells for which well-header ground elevation values are correct, but for which the DEM data for that well location are incorrect. It also may not have detected relatively small errors in either ground or KB elevation data for a well, as long as those values met the screening criteria. It did, however, detect large errors in well-header KB or ground elevation data.

Data were then screened for both global and local outliers. Outliers are those values that are outside a specified normal range compared with the entire dataset (global outliers) or within a local area (local outliers). If outliers are caused by error, they can have a detrimental effect on the accuracy of an interpolated surface and should be either corrected or removed before modelling the final surface.

Outliers may result from one or more of the following factors:

- incorrect ground elevation and/or KB elevation data not detected during the initial screening
- incorrect location data for a well
- deviated wells that are not marked as such and have either incorrect surface or bottom-hole location data
- incorrect stratigraphic pick data due to picking (human) error
- geological structure

A variety of geostatistical methods was used to identify outliers, including examination of neighbourhood statistics, inverse distance weighting interpolation and Voronoi maps. Outliers were flagged and the well data and geophysical logs examined to determine whether the outliers were due to geological variability or incorrect well data. In cases where no error could be identified, additional data were gathered to refine the definition of local structure. If a stratigraphic surface anomaly caused by a single outlier remained and no geological evidence was present to corroborate structure, then the outlier was removed.

Once initial outliers were either removed or confirmed, the outlier screening process was repeated at least three times. This iterative process was able to identify increasingly subtle outliers. As each pick was made during this project and all statistical outliers were examined and some removed, the largest source of error and uncertainty in the elevation of the stratigraphic surfaces is likely related to the surveyed KB (and ground elevation) for a given well.

8 Modelling Methodology and Results

A structure contour map for the top of the Horseshoe Canyon and Wapiti formations based on the stratigraphic picks made during this study is included to illustrate regional structure (Figure 13). This surface was modelled in preference to the Battle Formation top as the Battle Formation is locally absent owing to erosion at the base of the Scollard Formation. For the regional structure surface, the picks were modelled with Petra software using the highly connected features (least-squares) method.

The contours indicate a general southwestward dip of the structure surface north of Calgary. Dips are very gentle at approximately 0.3° (100 m per 20.5 km). The curving of the contours to trend west at the northern end and south-southwest at the southern end of this region was noted by Dawson et al. (1994b, Figure 24.14) on their structure contour map on the Battle/Kneehills Tuff marker and was thought to suggest a “downwarping of the basin along a northeast-southwest axis immediately southwest of Edmonton.” The contours swing again to trend south-southeast to the south of Calgary and, as noted by Glombick (2010) for the top of Belly River Group structure surface in this area, the dip of the top of the Horseshoe Canyon Formation is substantially steeper here than farther north. The structure surface also

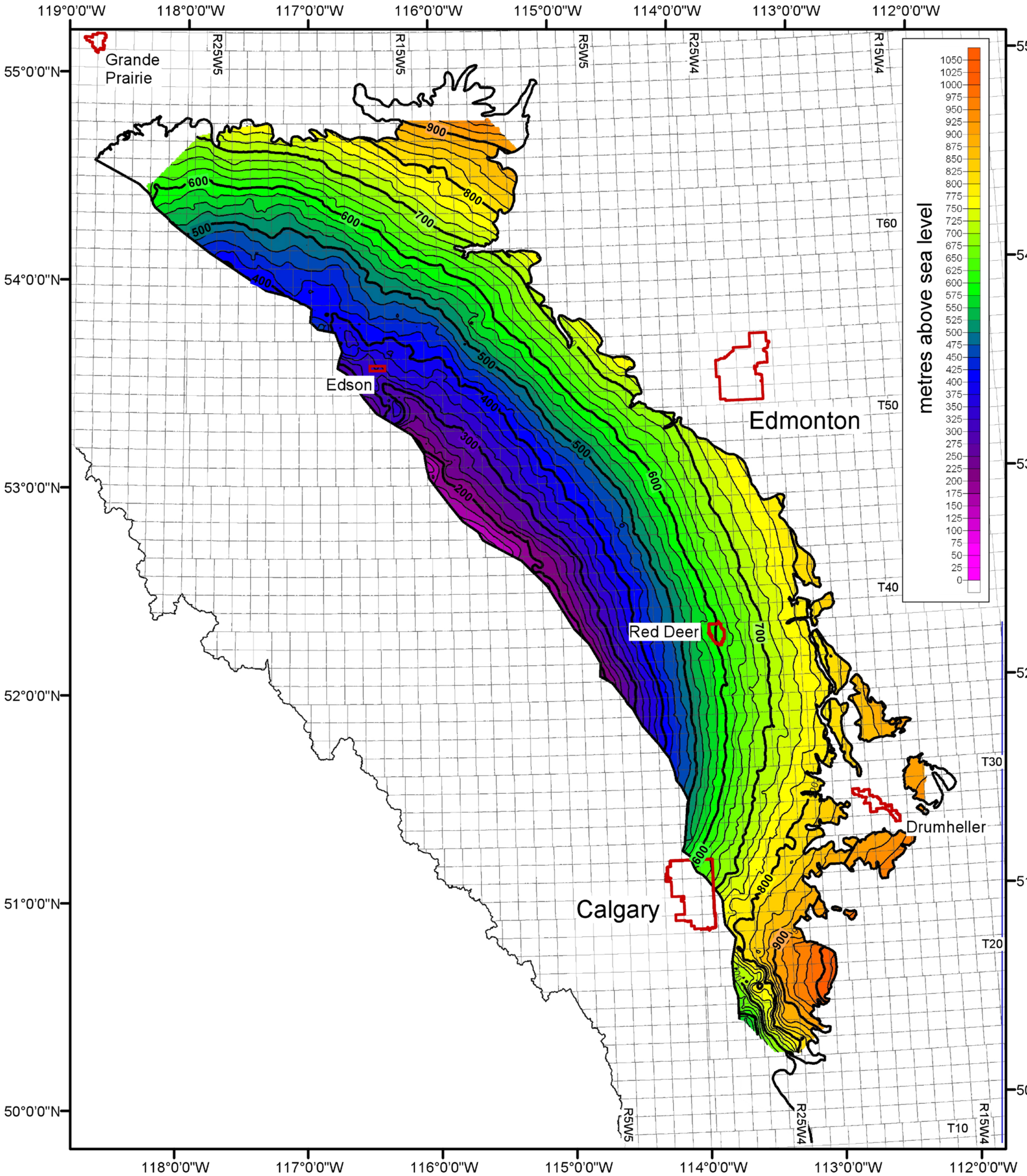

Figure 13. Shaded structure contour map of the top of the Horseshoe Canyon and Wapiti formations. Contour interval is 25 m; contour values are elevation in metres above sea level. Contoured area is bounded by the mapped top of the Horseshoe Canyon (St. Mary River Formation south of Twp. 17) and Wapiti formations from Hamilton et al. (1999), or the limit of data distribution. Major urban areas are outlined in dark red.

shows part of the ‘sawtooth’ pattern noted by Glombick (2010) in this area (Twp. 15 to 20), which may indicate fault-related offsetting of stratigraphic contacts perpendicular to the regional structural trend.

Northwest-striking linear reversals of dip in the Edson area (Figure 13) suggest faulting or folding extending 30 km to the northeast of the mapped limit of main cordilleran deformation (Hamilton et al., 1999). Using well log–based mapping and three-dimensional seismic data, Hart et al. (2007) detected northwest-striking, fault-related, low-relief anticlines at Cardium Formation and overlying stratigraphic levels in the Smoky River area, 200 km to the northwest of Edson. The structures described by Hart et al. (2007) extend in the subsurface for at least 50 km to the northeast of the nearest exposed thrusts mapped in the foothills and are thought to have developed over northeast-directed blind thrusts. It is possible that similar structures are present in the Edson area, although more detailed mapping of surfaces at lower stratigraphic levels would be required to confirm this.

9 Summary

A new, internally consistent set of subsurface stratigraphic picks for the top of the Horseshoe Canyon and Wapiti formations in 8863 wells and for the top of the Battle Formation in 8145 wells was made using geophysical well logs. Well data were screened for potential errors in KB and ground elevation data, as well as for errors in true vertical depth resulting from deviated wells. Local and global outliers were identified using statistical methods and either rejected or confirmed. Detailed picking helped to delineate areas where the Battle Formation is absent and the top of the Horseshoe Canyon and Wapiti formations coincides with the base of the overlying Scollard Formation. A modelled surface shows regional structure on the top of the Horseshoe Canyon and Wapiti formations in west-central Alberta.

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